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Optical noise reduction using partial coherence in spatial filtering for image detail enhancement

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OPTICAL NOISE REDUCTION USING PARTIAL COHERENCE IN SPATIAL FILTERING FOR IMAGE DETAIL ENHANCEMENT

by

Steven Musser

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the School of Photographic Arts and Photography of the Rochester Institute of Technology

September 1981

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MASTER'S THESIS

This is to certify that the Master's Thesis of Steven L. Musser has been examined and approved by the thesis committee as satisfactory for the thesis requirement for the Master of Science degree.

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ABSTRACT

Coherent optical spatial filtering can be used to increase the contrast of fine detail in photographs. The images produced, however, contain optical noise blemishes that make the procedure seldom usable in practical photography. A promising method of reducing the optical noise by means of partial coherence in a projection printer has been investigated involving the use of a plurality of point sources.

It has been demonstrated, using pictorial enlargements, that subjective sharpness levels may be obtained which are similar to those obtained by using specular illumination while greatly reducing the amount of coherent noise on the image. Enlargements of a sine wave negative have demonstrated the contrast enhancement produced by spatially filtering the zero-order diffraction pattern of the point source array.

I. Introduction

The contrast of the fine detail in a photographic image generally can be enhanced by optical spatial filtering using a coherent optical system designed for that purpose. The enhanced image is, however, likely to be marred by a number of blemishes caused by coherent optical noise.

The main purpose of this study was to explore and evaluate a promising method of reducing the optical noise, while allowing spatial filtering to be performed. This method makes use of a multiplicity of point sources in place of the single point source of light normally adopted for spatial filtering experiments. This technique, involving partial coherence, is applicable to projection enlarging systems.

Spatial filtering[1-8] is usually carried out by means of a point source of light (consisting of a pinhole illuminated by a laser, mercury arc, or other high-intensity source) and an optical system in which a film negative or film positive is imaged onto a photographic recording material. If the lens system is of good quality, a diffraction spectrum of the negative or positive is found in the plane containing the image of the pinhole. This spectrum is, under certain optical conditions, an accurate Fourier transform of the image on the film. The information is transformed from the space domain to the spatial frequency domain.

A spatial filter is defined as any means used to change the amplitude or phase of the light passing through the plane of the diffraction spectrum (the Fourier transform plane)[9].

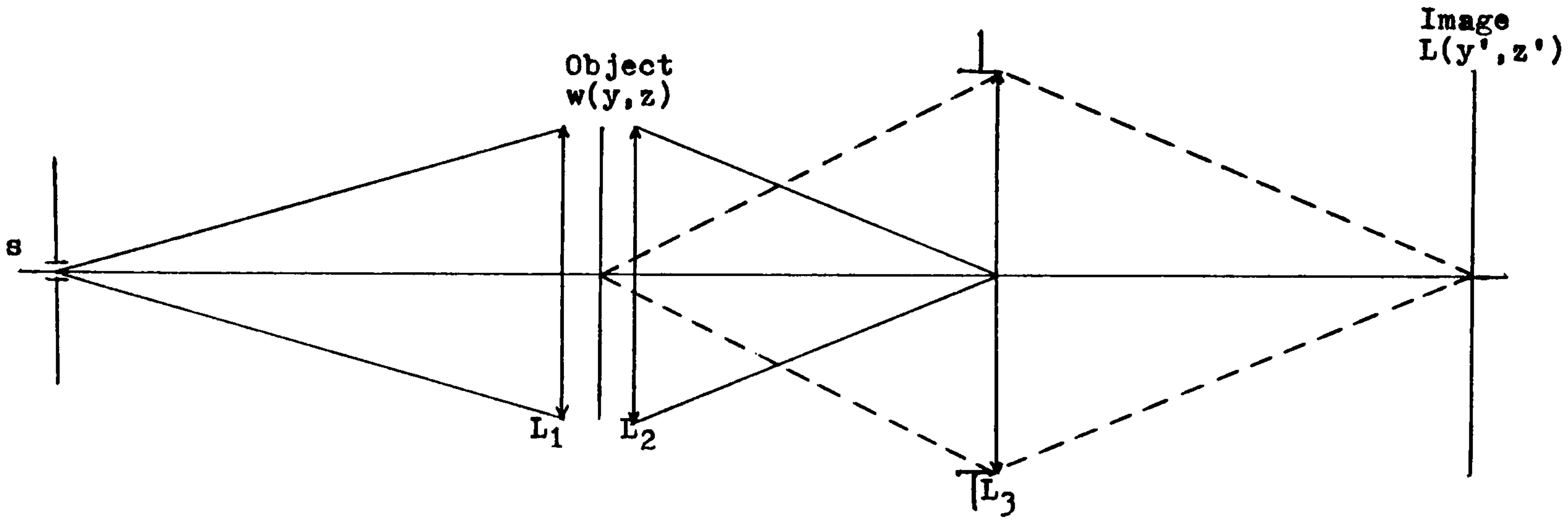
Andre Marechal[10], in the 1950's, demonstrated the use of spatial filtering in his work with a double diffraction system. He used a single point source in the system to obtain an approximation of the Fourier transform of a pictorial negative. The image of the negative could then be modified by filtering either the amplitude or phase of the spectrum.

In Marechal's system (Figure 1, page 3) the pinhole, s, is imaged near lens L_3, and the negative or object, w(x,z), is imaged at L(y',z'). The Fourier transform of w(y,z) is found near L_3 caused by the diffraction of light at aperture L_2. The diffraction of light at aperture L_3 then gives the image of the object at L(y'z').[11]

Marechal used a filter to absorb some of the zero-order light in the spectrum and also some of the adjacent diffracted light representing the very low spatial frequencies in the negative. The other diffracted light was transmitted by the filter. He was thereby able to enhance the contrast of the small details in the final image without changing the large-area contrast.[12]

Image sharpness measurement studies, such as those reported by Nelson and Higgins[13], make it evident that the enhancement of detail contrast by spatial filtering could be expressed quantitatively by comparing

Figure 1 Marechal double diffraction optical system (Reference 3, Figure 4)



the modulation transfer functions (MTFs) of images produced with and without the spatial filter.

The MTF for a projection printing system using a diffraction limited projection lens is shown in Figure 2, page 5 for both coherent and incoherent light. An example of the MTF obtainable using a coherent system and a particular spatial filter is shown in Figure 3. An estimate of the kind of MTF enhancement that may be possible with a partially-coherent system using a multiplicity of point sources is shown in Figure 4.

The enhancement of the image is expressed by the MTF as an increase in modulation at the different frequencies. Since the subjective sharpness values of images that are not excessively grainy have been found to be related to the area under the system MTF[14,15] (including the eye), we might expect that the enhancement of a projection printer's MTF by spatial filtering may also give an increase in image sharpness if the filtering does not increase the image graininess too much.

It is evident from a comparison of Figure 4 with Figure 3 that the use of a partially-coherent system with a multiplicity of point sources is likely to give a much higher resolving power than the use of a coherent system with a single point source[16], and this advantage is retained when spatial filtering is applied. It is also likely that spatial filtering with the partially-coherent system may give a somewhat lower resolving power than is obtainable with a completely incoherent

Figure 2 MTF curves for coherent and incoherent light

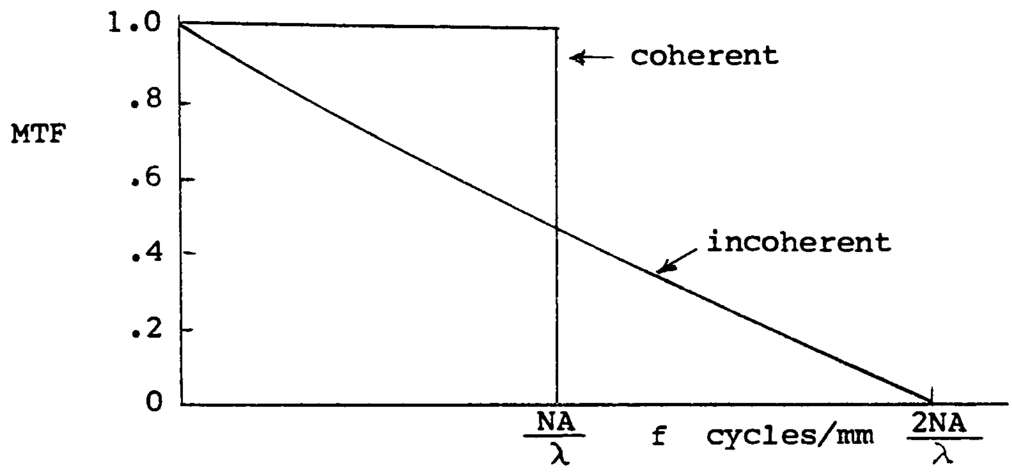


Figure 3 MTF enhancement using coherent light

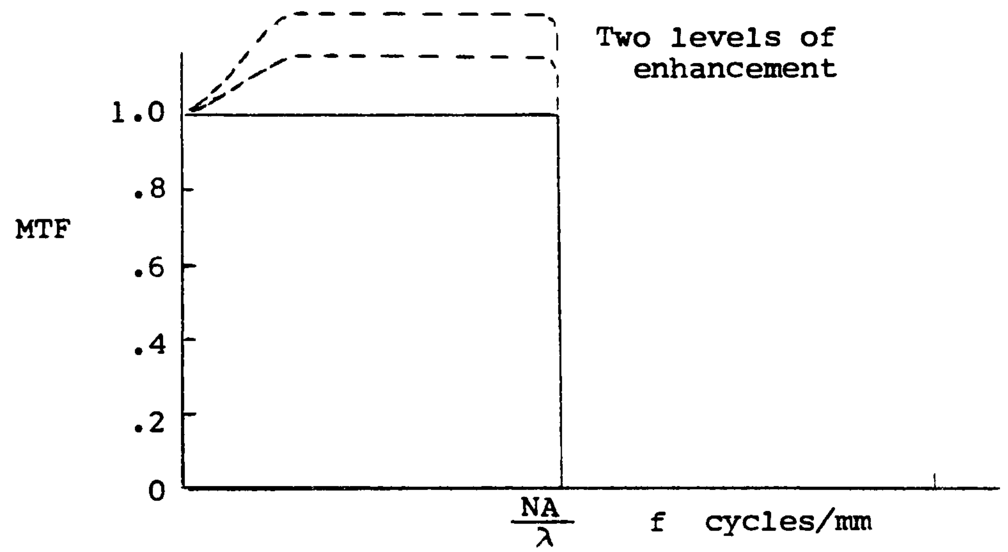
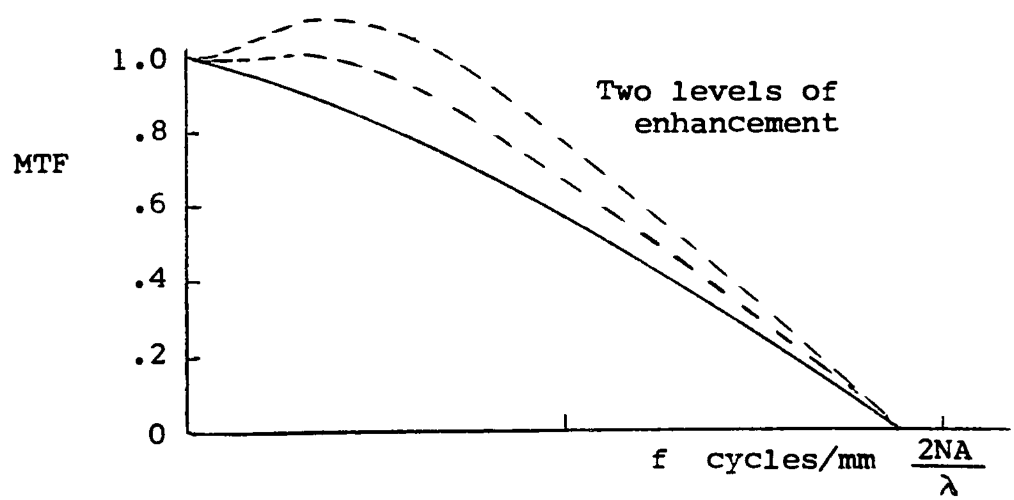


Figure 4 MTF enhancement using partially-coherent light



system (where no spatial filtering of this type is possible because the zero-order light completely fills the projection lens and overlaps the diffracted light).[17]

Previous work with optical spatial filtering of photographic images utilized a pinhole illuminated by a laser, a mercury arc, or some other kind of high-intensity source.[18-26] Lasers offer a very high degree of coherence, both temporally and spatially. This high degree of coherence gives a very sharp Fourier spectrum in the diffraction plane of the optical system, which makes the task of isolating discrete frequencies for filtering easy.[27] Point sources radiating polychromatic light (white light), on the other hand, offer only spatially coherent (laterally coherent) light.[28] The lack of temporal coherence in this light gives a slightly blurred Fourier transform because light of different wavelengths images the diffraction spectrum at different locations. Only the zero-order light remains in one location. This poses a problem only when a high degree of discrimination in the spectrum is necessary for filtering.[29,30]

A major disadvantage in using a point source is that, unless a highly intense light source is utilized, the light intensity on the enlarging plane is insufficient to provide acceptable exposure times. Nelson[31] used an "oversized" pinhole source, 0.5mm to 1.0mm in diameter, which illuminated the object with partially coherent light. This enlarged point source allowed a greater amount of light into the system, but, because of its reduced degree of coherence, blurred the diffraction spectrum. This distortion of the spectrum made it difficult to filter discrete frequencies. Sharp discrimination between neighboring spatial frequencies was, however, not required for the kind of filtering he wished to do for the enhancement of fine-detail contrast.

In addition to allowing more light into the system, the oversized pinhole tended to give less coherent noise on the final image due to the partially-coherent nature of the light.[32] Still, the amount of coherent noise produced by Nelson's "point-source" projection enlarger system was substantial enough to warrant his investigation of other methods of eliminating the noise problem.

Coherent noise in the optical system was evidenced as edge fringing and shadow blemishes on the photographic image.[33] These defects were caused by the interaction of coherent or nearly coherent light with sharp edges on the negative (fringing) and by foreign material on or in the lenses and other elements of the imaging device. The edges on the negative were high contrast areas in the scene[34], and the foreign material was dust, dirt, scratches, and bubbles on or in the components of the optical system. The spatial coherence of the light source caused high contrast shadows of the foreign material to be cast on the enlarging plane.[35] These blemishes greatly detract from the quality of the enlarged image.

Attempts have been made to alleviate optical systems of coherent noise. Thomas[36], in 1967, devised a means to average the noise over the entire image plane by moving the point source and the filter synchronously during exposure. Horner[37], in 1974, reported on noise reduction by moving the negative and the print material. In 1970, Grebowsky[38] and a group of researchers at Goddard Space Flight Center also reported the reduction of blemishes using a noise averaging technique. Their system involved rotating the lenses. These three methods each demonstrated a reduction of coherent noise, but each was susceptible to problems due to vibration and misalignment.

Nelson devised[39] a method of limiting the amount of coherent noise by using a plurality of light sources to illuminate the object. (see Figure 6, page 12) This method, based on Abbe's "Theory of the Microscope" (see Appendix A), still allowed spatial filtering. The array of oversized pinholes reduced coherent noise by using the same principle as in moving either the point source or the optics during exposure, that is, spreading the shadow positions over the whole image. Nelson reported that, for a foreign particle in the optical system, each source casts a separate shadow that is displaced from the other shadows on the image. If n oversized pinholes were used in the source array, the contrast of each shadow on the image was approximately one-nth of the contrast obtained using a single oversized pinhole. As n was increased, the shadows became less distinguishable. As n became very large, the shadow noise and the ringing effects disappeared.

Zernike[40], in his Nobel Prize winning work with microscope applications of his phase contrast method, first used a ring source with a spatial filter. His technique is the same as Nelson's ring of n filters, if n is infinity. The two techniques differ mainly in that Zernike used both amplitude and phase spatial filtering while Nelson used only amplitude spatial filtering. Zernike's aim in using this scheme was to diminish haloes and other optical noise in his microscope image. He reported that, by using this ring-source/ring-filter combination, the noise was spread out over the image field, and thus became less visible. Nelson suggested that, by using the ring source (or a ring of numerous point sources) and accompanying amplitude spatial filter in conjunction with his projection enlarger system, the fine-detail contrast of enlarged photographic images could be enhanced while minimizing coherent noise. The filtered ring source was not attempted in this study.

The object of this study was to investigate the problems involved in constructing a spatial filtering system and producing pictorial images which show contrast enhancement while reducing the amount of coherent noise obtained when using conventional methods of photographic projection enlarging.

II. Experimental

Optical System

The optical system used for this study is shown in Figure 5, page 11. (see Appendix B for specifications) A 500 watt, 120 volt, tungsten filament lamp is housed in an Argus Model 541 35mm slide projector. A Rohm and Haas Plexiglas diffuser having a diffuse transmittance of 22% is positioned on the lamp side of a 35mm slide mount located in the slide holder of the projector. The lamp illuminates the diffuser via a set of condenser lenses in the lamp housing. The diffuser acts as the light source for the optical system, eliminating the possibility of images of the lamp filament occurring near the critical focusing planes in the enlarging system.

A Bausch and Lomb 6 in., f/2.5 relay lens images the diffuser at 2x on the source side of the condenser lens.

The light source template (see Figure 6, page 12) acts as the light source for the enlarging system. The final enlargements made in the investigation used a template with 0.70mm diameter pinholes.

The condenser lens is an Ealing 76mm, f/2.0 achromatic doublet. This lens focuses a 0.28x image of the template onto the filter plane. The filter plane is where the diffraction spectrum of the condenser lens aperture occurs. The zero-order diffraction spectrum appears as the image of the

Figure 5 Optical system

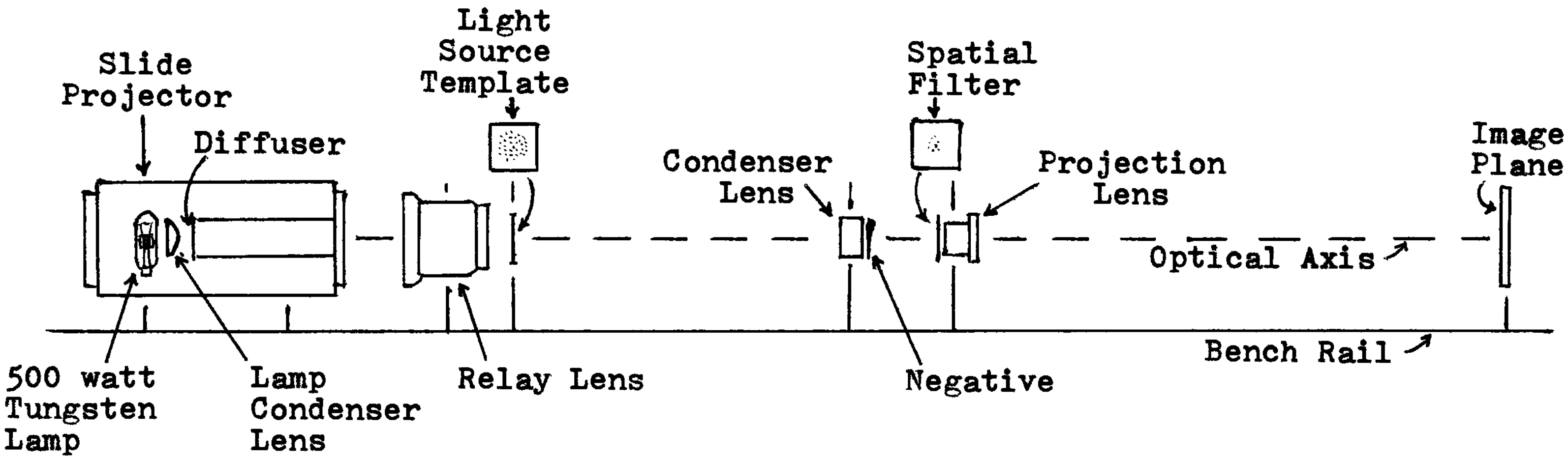
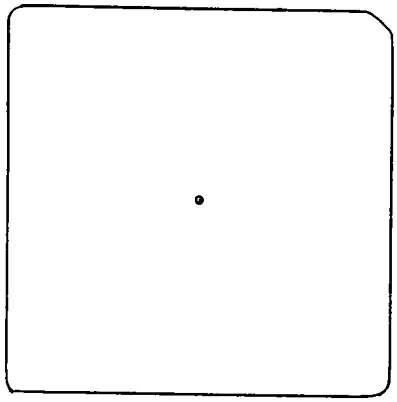
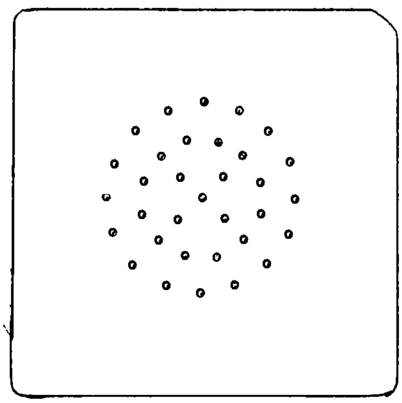


Figure 6 Light source templates

a) Single point source



b) Thirty-three point source array



template pinholes and is aligned with the filter spots by using a micrometer having x-y travel to move the template.

The 35mm negative is sandwiched between two metal platens having 15mm x 40mm apertures. This assembly is securely positioned on the image side of the condenser lens.

The projection lens is a Fujinon 90mm, f/4.5 enlarging lens. The final experiment exposures were made with the projection lens aperture at f/8.0, which allowed the zero-order diffraction spectrum to pass through the aperture without vignetting. The projection lens images the negative onto the image plane at approximately 5.3x. The magnification of the negative on the image plane depends on the focusing distance of the image, which changes when a filter is not in the light path.

The enlarged images were recorded on 4 x 5 in. Kodak Commercial Film No. 6127. (see Appendix C for plate and film processing)

Spatial Filters

The initial filter plates used were Kodak projector slide plates which were used to determine problems with alignment and to study the exposure characteristics of high resolution plates. No enlargements were made with these filters.

The filters used to produce enhanced images were exposed on Kodak High Resolution Plates, Type 1A, coated with emulsion 649-GH. This emulsion is sensitive to the blue and into the green portion of the visible light spectrum.

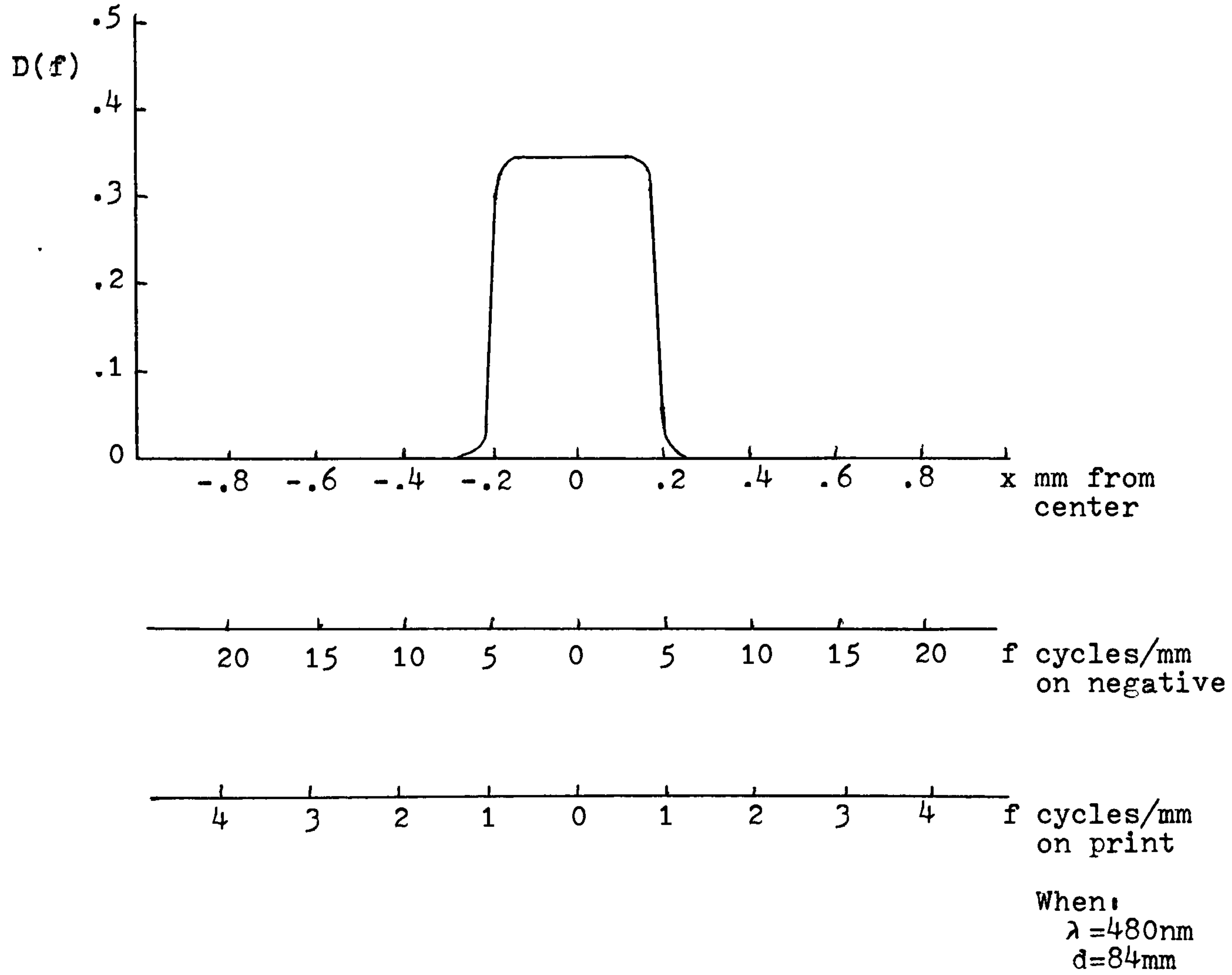
The densities of the filter spots were found to differ between the neutral and blue density measurements. The blue density was a factor of approximately 1.3 greater than the neutral density. The Kodak Commercial Film is blue sensitive only, so that it was necessary to know the blue density of the spatial filter because the filter density was important in the determination of an optimal filter to use for exposing the final enlargements.

The final filters were exposed using a light source template having a full array of thirty-three, 1.6mm pinholes. The filter spots were then approximately 0.5mm, which better facilitated the alignment of the filter with the zero-order diffraction spectra produced with the 0.7mm pinholes. (see Figure 7, page 15 for the density profile of the filter used)

Negatives

Two different negatives were used to make the enlarged images. The primary negative used was a pictorial negative of Building No. 82 in Kodak Park, Rochester, New York on 35mm Eastman Fine Grain Panchromatic Motion Picture Film 5234. The pictorial images were used to make subjective comparisons while investigating the best filter density, and also to compare enlargements

Figure 7 Density profile of the spatial filter, D(f)



exposed with the following illumination:

1. Diffuse source.
2. Specular source using a single 0.70mm pinhole.
3. Unfiltered point source array (33 pinholes).
4. Spatially filtered point source array (33 pinholes).

A 3x reduction of Robert Lambert's[41] transmission sine wave target on 35mm Kodak Panatomic-X Film 5240 was enlarged with and without a spatial filter to determine the enhancement due to spatial filtering. The neutral density patches on the negative were used to determine the Density versus Relative log Exposure for the two enlarged images.

Determination of Enhancement Factor

The amount of MTF enhancement in a spatially filtered enlargement versus an enlargement made without the spatial filter is given theoretically by the enhancement factor.

$$E(f) = \frac{t_a(f)}{t_a(f=0)}$$

where $t_a(f)$ is the amplitude transmittance of the filter at spatial frequency, f, in cycles/mm, and

$$t_a(f) = \sqrt{t_i(f)}$$

where $t_i(f)$ is the intensity transmittance at f, and is equal to the antilog of D(f), the density of the filter at f. (see Figure 7, page 15)

According to diffraction theory, the spatial frequency is related to the distance from the zero-order diffraction beam, x, by

$$f = \frac{x}{\lambda d}$$

where λ is the wavelength of light and d is the distance from the negative to the spatial spectrum. (84mm in this system)

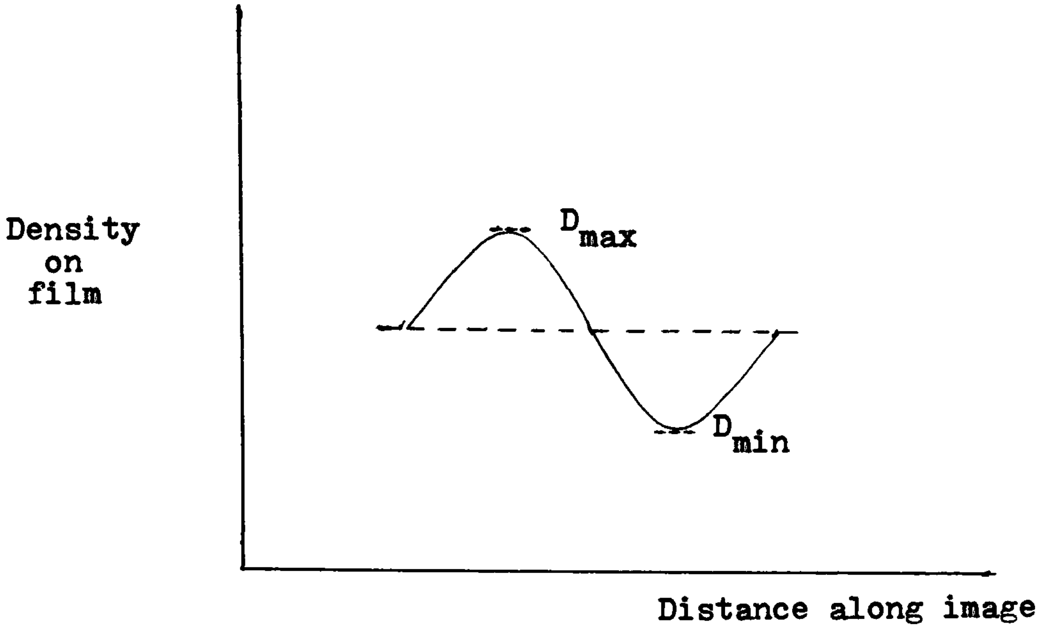
The enlarged images of the sine wave targets were scanned by a Joyce-Loebl Isodensitometer MK III CS to determine the modulation of each frequency. This was done by determining D_{max} and D_{min}, the maximum and minimum densities for each frequency on the micordensitometer trace of the sine wave images. (see Figure 8, page 18) The density values were then converted to log Exposure units so that the effect of the Commercial Film characteristic curve would not be seen in the final result. This would not be necessary if the characteristic curve of the filtered and unfiltered exposures were identical, because the effects of the curve shape would cancel when the enhancement factor was calculated.

The log Exposure values were then changed to intensity transmittance, t_i, because the sine wave images are sinusoidal in transmittance and not in log Exposure or in Density.

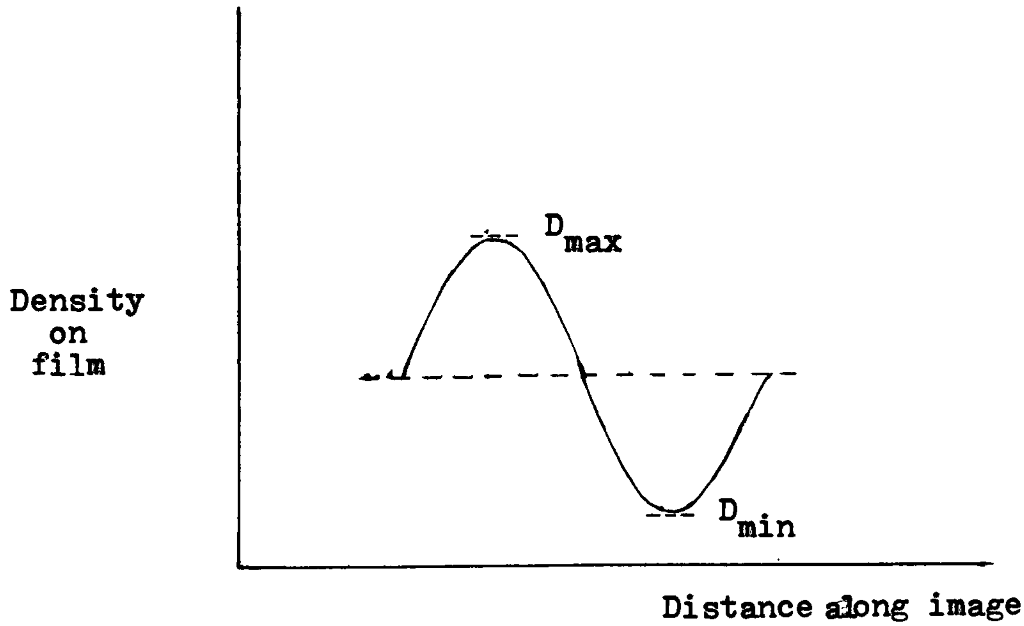
The modulation at each sine wave frequency was

Figure 8 Microdensitometer traces

a) Without spatial filter



b) With spatial filter



then calculated by

$$\text{Modulation} = \frac{t_{max}-t_{min}}{t_{max}+t_{min}}$$

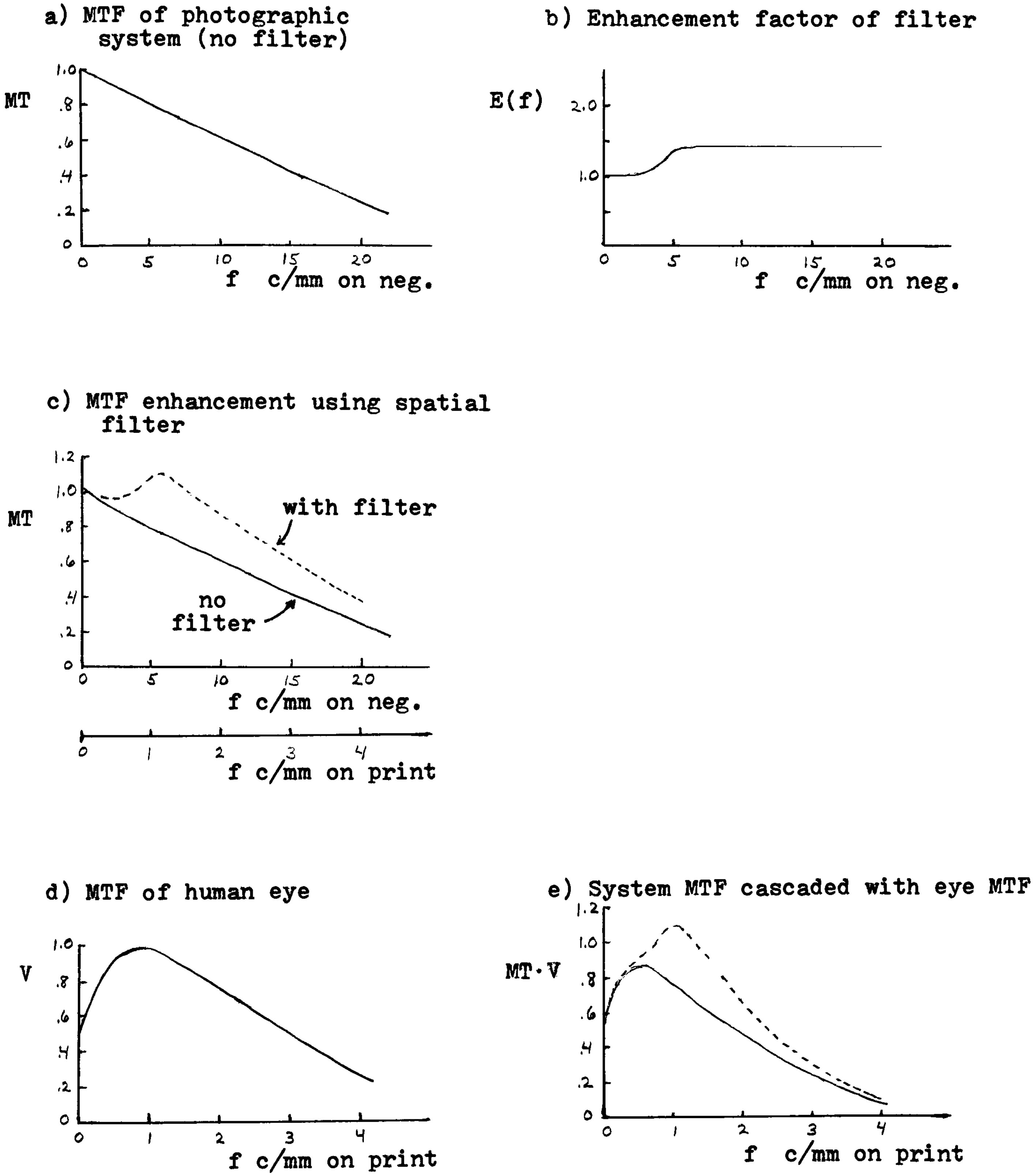
The enhancement factor was determined from

$$E(f) = \frac{\text{Modulation with filter}}{\text{Modulation without filter}}$$

The function E(f) was multiplied by a typical system MTF curve to show the improvement in the system by using spatial filtering.

Using the filter density profile in Figure 7, the Theoretical Photo-system Analysis shown in Figure 9, page 20 may be constructed.

Figure 9 Theoretical photo-system analysis



III. Results

Effect of Varying the Filter Density

When making the spatial filters from the High Resolution Plates, the initial aim was to obtain a spot density of approximately 0.60. (The Q factor for the 649-GH emulsion is approximately 1.0) After some experimentation with the filter exposure, using the full thirty-three point source array, a filter with a spot density of 0.64 was produced. (the spot densities were measured by microdensitometer trace.) Enlargements of the pictorial negative were then made with and without the spatial filter. The filtered enlargement appeared to have dark areas in the image detail which normally should have been lighter in density relative to the density of the other detail. Shadows cast by dust specks on the negative appeared very dark on the image. Dust noise is normally evidenced as spots of very low density on images exposed using partially coherent illumination. This phenomenon was diagnosed as overmodulation caused by the enhancement of the image modulation to a value greater than 1.0. (see Appendix D)

A new filter having spot densities of 0.48 was prepared and enlargements made. Overmodulation, although less appearant, was still present on both the image detail and dust noise of the filtered exposure. The next spatial filter fabricated had a density of 0.35. The filtered enlargement had only a trace of overmodulation in the detail of the photograph, but overmodulation of images of dust particles on the negative was still a problem. Some dark blemishes on the negative imaged as spots of low density, as would be expected. This was likely because these blemishes were not opaque, as are dust particles, but allowed some light to reach the image plane, and so, did not exhibit as much overmodulation.

The center pinhole in the 0.70mm pinhole template was drilled to 2mm in diameter. An enlargement of the pictorial negative was made using the spatial filter used previously. The larger central light source overlapped the center spot on the spatial filter plane. The image produced using this arrangement exhibits less overmodulation, but with a loss of sharpness relative to the original filtered image.

No further studies were done concerning the filter spot density and its effect on overmodulation in the image. It is conceivable that further investigation would demonstrate that a filter of lesser density, possibly 0.20 to 0.25, would produce perceptibly enhanced images while alleviating the problem of overmodulation.

Phase Noise

Another problem which surfaced during the investigation of the effects of filter spot density was the presence of phase noise in the enlarged images. Phase noise is evidenced as a general distortion, or blur, in the photograph. This is either caused by an irregular emulsion surface on the negative or filter, or by variations in the refractive index across the negative or filter. These irregularities cause a shift of the phase portion of the diffraction spectrum, so that the image of the negative is not properly reconstructed at the filter plane. Nonuniform emulsion surfaces usually occur because of the increase of the emulsion thickness in the dense regions of the image where much development has taken place. Due to the difference in the refactive indices of the emulsion and air, the imaging illumination propagates through unequal optical path lengths enroute to the image plane, causing a displacement of the phase spectrum, and thus, blurring the final image.

The problem was eliminated by immersing the negative and the filter in a petroleum-based oil (mineral oil) of refractive index similar to that of photographic gelatin (1.5). Some improvement was seen in the phase noise when just the filter was in oil, but a dramatic improvement occurred when both the filter and the negative were immersed in the oil.

Phase shifts in the diffraction spectrum may also be a result of hardening, or "tanning", of the gelatin in dense areas of the negative where much development has taken place. The hardening of the gelatin causes a change in the refractive index of the gelatin relative to areas where little development has happened. The process of tanning involves the chemical reaction of oxidized developer with the gelatin.[42] This can be avoided by using developers which do not contain very active developing agents such as hydroquinone or pyrogallol.

Comparison of Enlargements

Enlargements of the pictorial negative (in oil) were made to compare the image sharpness and coherent noise for the extremes of possible projection enlarger illumination systems. Four enlarged 4 x 5 in. images were produced, each by a different method of illumination. (see Experimental)

A visual comparison of the specular enlargement and the filtered enlargement concluded that the two images are very similar in sharpness. This is a remarkable result considering that the specular image contains much coherent noise (mainly from dust on the condenser lens and the enlarging lens) which detracts greatly from the quality of the image. The image exposed using the filtered array has some blemishes caused by overmodulated dust on the negative, but these do not render the image unsightly to the viewer. The comparison of these two enlargements is suggestive that the sharpness of a specular illumination system may be obtained without the abundance of noise that is associated with a coherent source. An added advantage in using the filtered array of point sources to enlarge negatives is that Abbe's theory (see Appendix A) predicts that the resolution offered by this illumination system will be greater than for a specular system.

The filtered exposure exhibits a dramatic increase in image detail contrast when compared to the enlargement made with the unfiltered point source array. This enhancement seems to be evidenced in most of the image detail. The quantitative enhancement for each spatial frequency will be discussed later.

The diffuse enlargement, as expected, seems to have less detail contrast than the other photographs. This image illustrates one extreme in the range of contrasts that can be obtained simply by changing from complete incoherence or diffusion to complete coherence or specularity in a projection enlarger. Although the overall picture contrast of the images increased with the specularity of the light source, the modulation enhancement seen in this series of enlargements remains independent of this overall image contrast, which is determined by the gradient of the characteristic curve of the photographic image as influenced by the Q-factor of the developed silver image and the degree of specularity.

The comparison of noise on the enlargements shows, as stated previously, that the specularly exposed image (made with a single point source) has the most blemishes. These are evidenced as haloing around the high contrast detail in the negative and are attributable to the high degree of coherence in the light used to expose the image. Hundreds of haloed dust shadows are seen on the image along with speckle noise, which is normally seen in photographs exposed with highly coherent radiation.

The image exposed using diffuse illumination contains very little noise of any kind. Traces of dust shadows can be seen, but do not distract appreciably from the quality of the photograph.

The image exposed using the unfiltered array contains some dust images which appear as white dots, but does not have speckle noise or haloing. This dust lies on the negative. The noise arising from dust on the lenses is eliminated by the use of the plurality of point sources in the array.

The enlargement made with the filtered array contains the same noise as the unfiltered image, but the dust on the negative produced black rather than white dots because of overmodulation.

A subjective analysis of the grain noise in each photograph was not attempted because the very fine grain of the negative does not allow the difference in the grain pattern of each image to be seen.

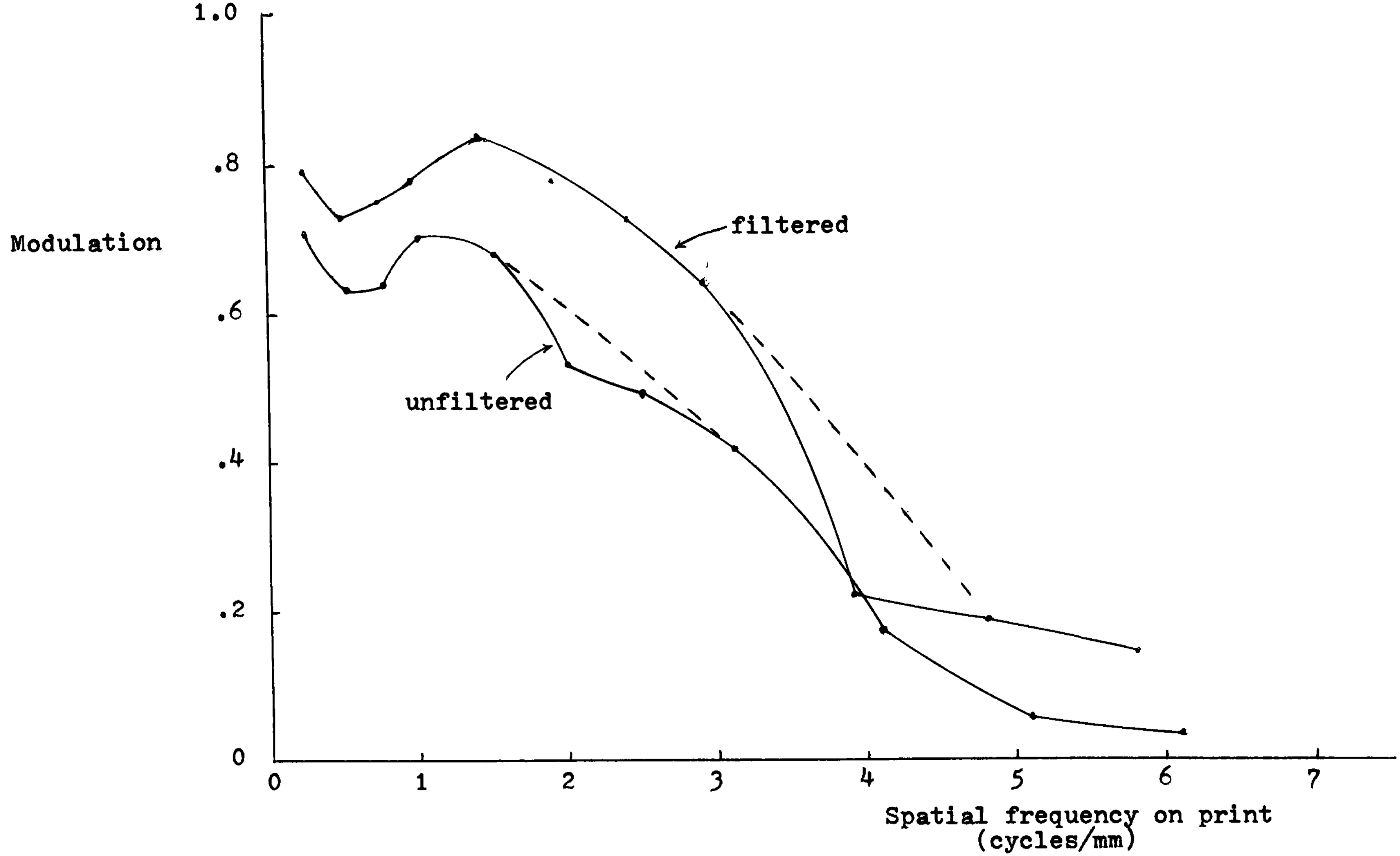
Enhancement Factor

Enlarged images of the 35mm sine wave target (in oil) were made using the point source array with and without the spatial filter. The modulation at each spatial frequency was determined by microdensitometer traces for both images. A plot of modulation versus spatial frequency for each image is shown in Figure 10.

It is apparent from the curves in Figure 10 that considerable enhancement of the modulation or contrast of the sine wave images has occurred as a result of the spatial filtering. At any given frequency, the ratio of the ordinate of the upper curve to that of the lower curve is the enhancement factor. The ratio is about 1.5, for example, at a frequency of 3 cycles per mm on the enlargements or about 15 cycles per mm on the negative. (A complete plot of the enhancement factor as a function of spatial frequency is given in Figure 11.a)

It should be noted that the curves of Figure 10 represent the output modulation of the sine wave image and should not be confused with the modulation transfer curves, which would be found by dividing the output modulation by the input modulation (the modulation on the negative) at each spatial frequency. The input modulation is the same for both the filtered and the unfiltered exposures so that in the calculation of the enhancement factor (described in the Experimental section) these divisors cancel.

Figure 10 Modulation versus spatial frequency for the filtered and unfiltered images



It should also be noted that the curves of Figure 10 are determined with a sample size of only one, because most of the time for this project was devoted to the difficult task of building and assembling the equipment. The curves of Figure 10 are expected to represent only the general trend of the enhancement and are not to be taken as statistically obtained quantities.

The plots in Figure 10 show a dip in the curve at low frequencies. The initial drop in modulation is due to flare light in the enlarging system used to reproduce the original sine wave target onto the 35mm Panatomic-X film. The rise at slightly higher frequencies is due to adjacency effects in the development of the 35mm sine wave target image. The increase in modulation at this point occurs because, during development, inhibitors produced in the emulsion areas with a high concentration of developable silver diffuse into the adjacent areas of low developable silver concentration. This allows more development in the high density area and less development in the low density area.[43]

The modulation at spatial frequency 3.9 cycles/mm appears to be an anomalous point, possibly because of an inconsistency in the modulation of the corresponding frequency in the original sine wave target.

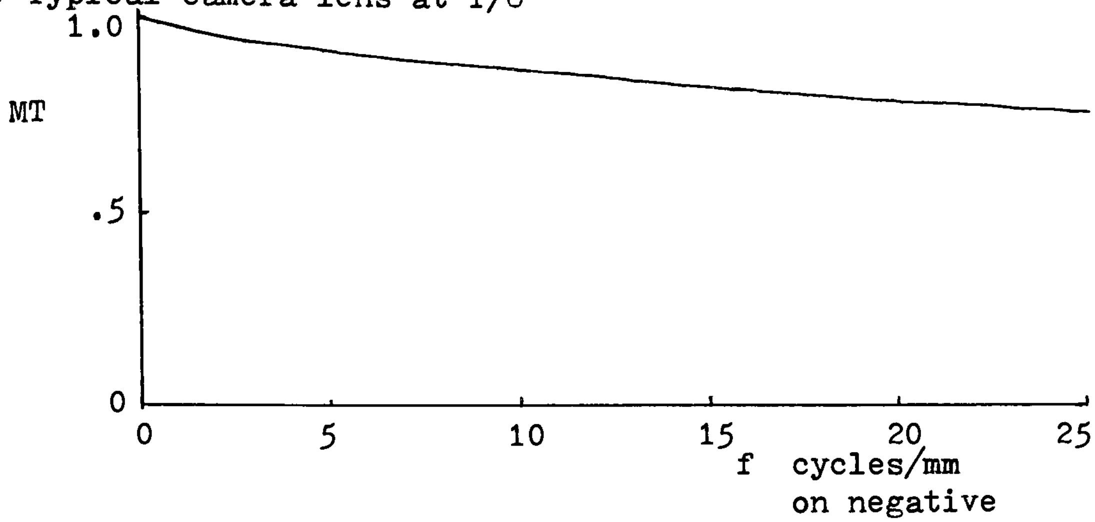
According to theory, the two curves should come together at high frequency and go to zero modulation at the same spatial frequency. The actual separation of the curves gives inflated enhancement factors at these high frequencies. If time had permitted, a statistically controlled experiment would have been done to determine whether these irregularities occurring at the higher spatial frequencies are due to errors in the system or the measurements, or are due to some unexplained phenomenon such as a phase shift in the filter at the higher frequencies.

The Photo-system MTF analysis using the experimentally determined enhancement factor curve is shown in Figure 11. The curves for the camera lens, 11.a, and the enlarging lens, 11.c, are typical of those used in practice. The camera film MTF is the published curve for Eastman Fine Grain Panchromatic Motion Picture Film 5234 developed in DK-50. The enlarging lens MTF does not take into account flare light which would lower the modulation. This effect would be most prominent in the low frequency areas.

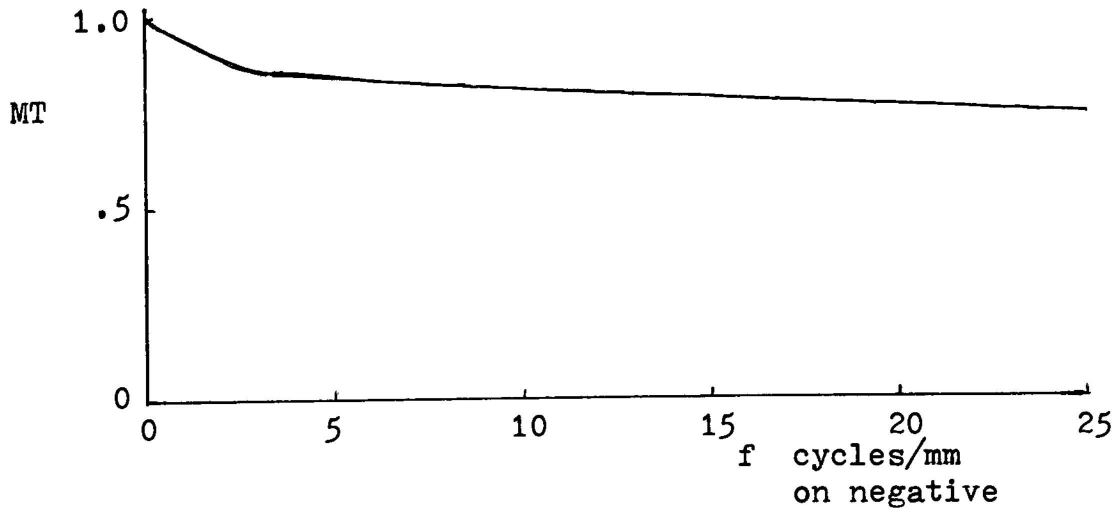
Curves 11.a, 11.b, and 11.c are cascaded to obtain curve 11.d, the system MTF. The enhancement factor determined experimentally in this investigation is shown in Figure 11.e This curve is multiplied by the system MTF to obtain the enhanced system MTF shown in Figure 11.f. The analysis may be completed by cascading curve 11.f with the eye MTF shown in Figure 11.g. This would give the modulation transfer seen by the viewer.

<u>Figure 11</u> Photo-system Analysis

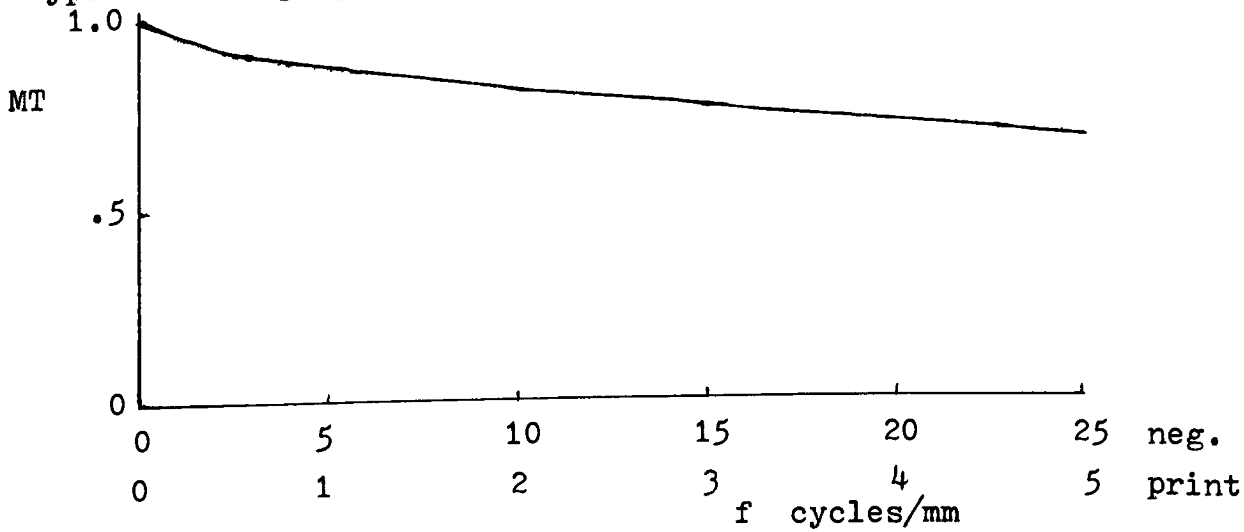
a) Typical camera lens at f/8



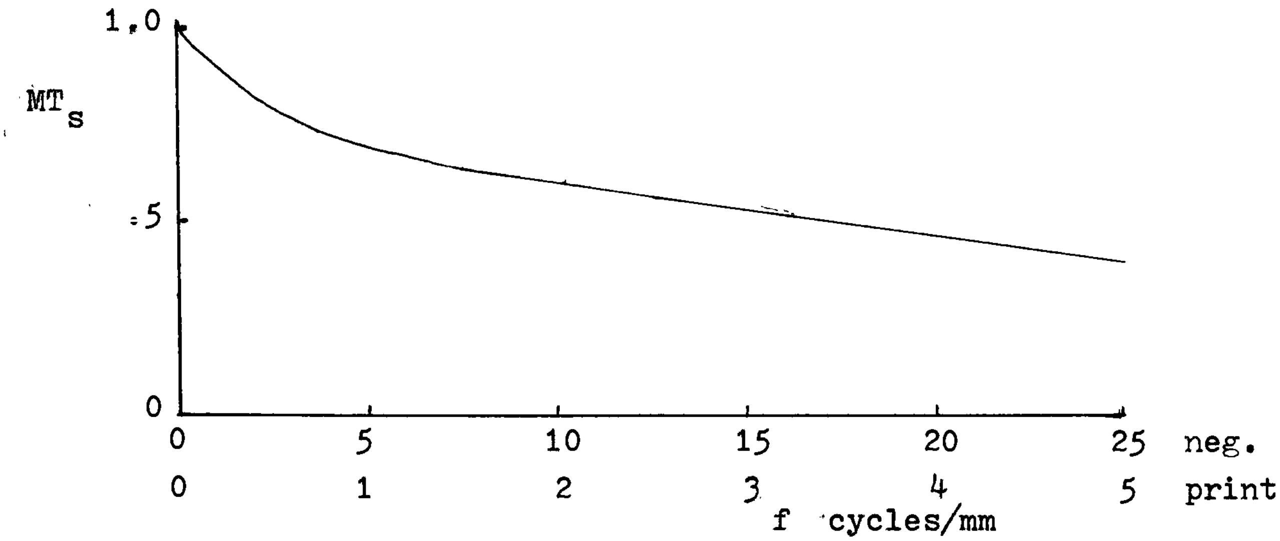
b) Eastman Fine Grain Panchromatic Motion Picture Film 5234



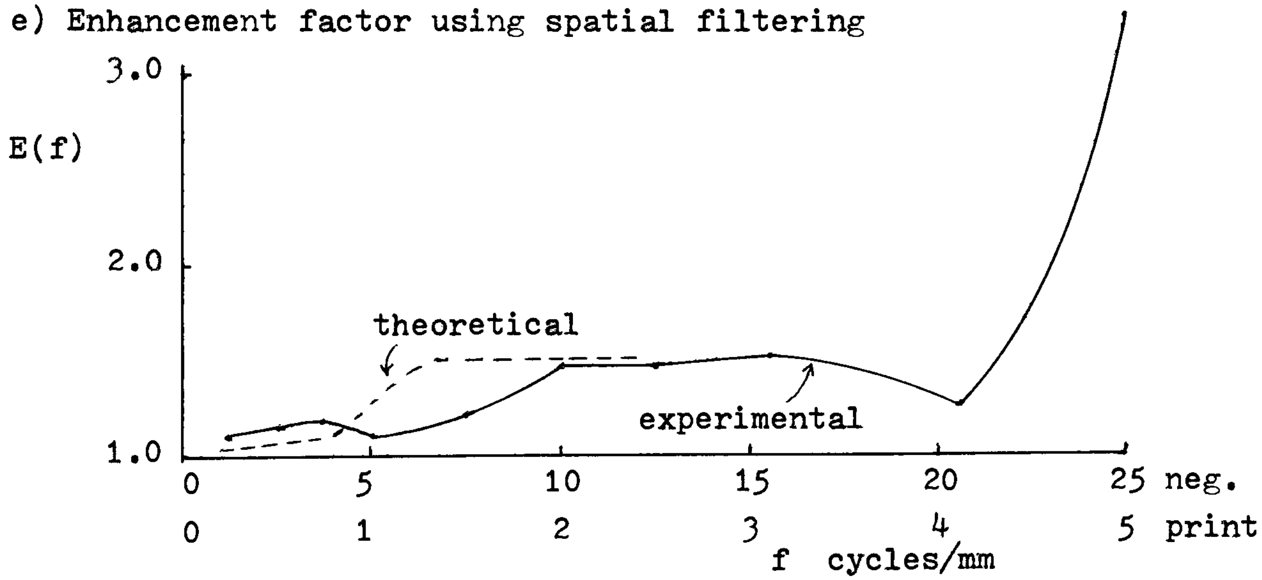
c) Typical enlarging lens at f/8



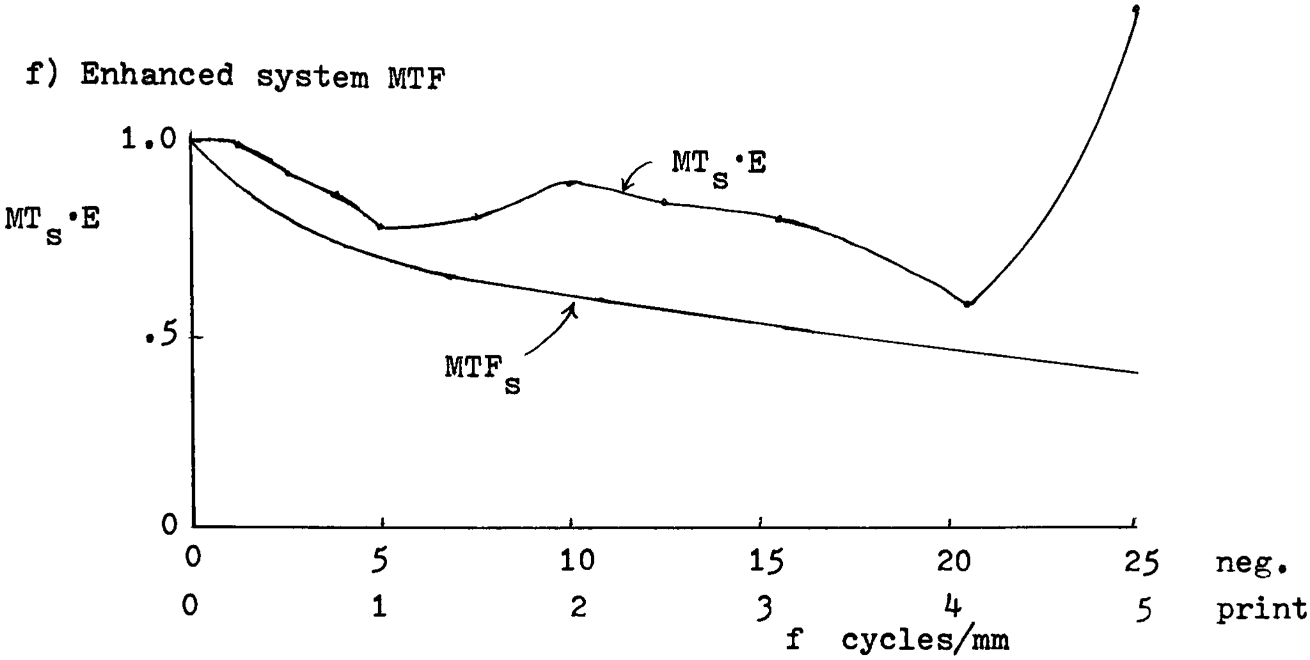
d) System (cascaded MTFs)



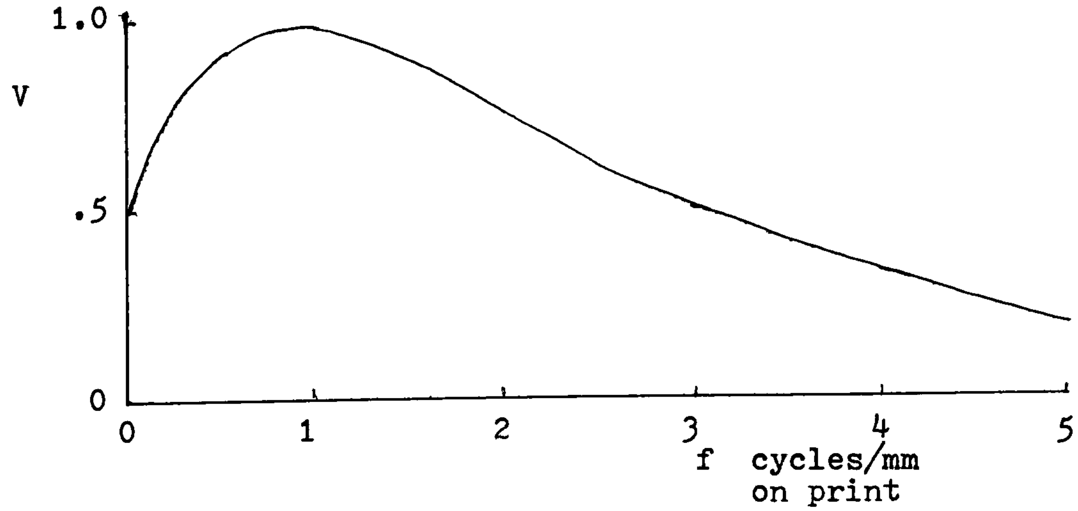
e) Enhancement factor using spatial filtering



f) Enhanced system MTF



g) MTF of the eye



IV. Conclusions

1. Enlargements may be produced having image detail contrast levels similar to those obtained in a specular enlarging system while having significantly less coherent noise on the image. The resolving power obtainable is approximately double that of a specular system and nearly equal to that of a diffuse enlarging system. (The latter gives lower contrast in detail of intermediate size.)

2. The method, which presently involves the use of a Kodak High Resolution Plate as a spatial filter in a projection printer with a plurality of point sources, requires that the photographic negative be immersed in a liquid having a refractive index in the neighborhood of 1.5. The omission of the liquid causes the relief structure in the negative to appear in the projected image plane as a low-quality image superimposed on the normal image.

3. The wave theory of interference and diffraction of light indicates that liquid immersion of the negative may almost ~~should~~ be unnecessary if the spatial filter introduces no phase shift. Consequently, any future study of this system probably should include an attempt to obtain a more perfect spatial filter than the one used here. The immersion liquid used on our filter to reduce the phase shifting effect of any relief pattern on the filter may not have had an optimum refractive index, or there may be a residual refractive index

variation within the filter that liquid immersion cannot correct.

4. The use of a filter made with a thin layer of evaporated metal, such as aluminum, on glass should be considered in future studies as a possible way of eliminating the need for liquid immersion of the negative.

5. The optimum transmission density of the spatial filter seems to lie within the range of 0.25 to 0.45 (where a density of 0.3 produces a substantial MTF enhancement factor of about 1.4.). Higher densities, such as 0.6 and 0.9 produce serious image blemishes presumably caused by overmodulation of the images of dust particles on the photographic emulsion surface, or by some phase shift effect not yet considered. Some of this trouble remains at a filter density of 0.45. Further study may reveal a solution.

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APPENDICES

Appendix A Abbe's Theory in terms of MTF

In 1873 Professor Ernst Abbe[6] proposed a theory which described the physical mechanism of image formation by a coherently illuminated optical system. Abbe's Theory of the Microscope, as the theory is sometimes known, predicted the diffraction spectrum (or Fourier transform plane) in Marechal's double diffraction optical system, and thus hypothesized the use of spatial filtering to either enhance or degrade photographic images. This theory can also be used to explain the formátion of images using an incoherent optical system in terms of the Intensity Modulation Transfer Function, MTF_I, of the optical system.

For either an incoherent or a coherent optical system the MTF_I is equal to the square of the Amplitude Modulation Transfer Function, MTF_A. MTF_I can be easily measured by microdensitometer traces of sine wave target images. The MTF_I for the coherent system is shown in Figure A1.c for the case in which the illuminating pinhole occurs on the optical axis, as in Figure A1.a, and, thus, produces the diffraction spectrum in the transform plane shown in Figure A1.b.

If the pinhole is moved to some position above the axis, as in Figure A1.a, the diffraction spectrum will appear as in Figure A2.b. The higher order frequencies of the diffraction spectrum will be lost due to vignetting of the system aperture. This will produce an MTF_I which will have a shape similar to that of Figure A2.c. Likewise, if the pinhole were moved off-axis horizontally, as in Figure A3.a, the diffraction spectrum, Figure A3.b, would contain higher order spatial frequencies than were obtained by using a pinhole centered on the optical axis (Figure A1) the MTF_I shown in Figure A3.c would result. If the pinhole were moved even closer to the edge of the aperture, as in Figure A4, the diffraction spectrum and resulting MTF_I would be as shown in Figures A4.b and A4.c, respectively.

By thinking of an incoherently illuminated aperture as an infinite number of coherent sources, the MTF_I of the optical system can be expressed as the average of all the MTF_Is for the infinite number of coherent sources. The MTF_I of the incoherently illuminated optical system is shown in Figure A5.

The MTF_I for an incoherently illuminated system may be closely approximated by using an array of one thousand or more pinholes to illuminate the optical system and averaging the MTF_Is of each pinhole to obtain a single MTF_I for the system.

The thirty-three semi-point source template approximates an incoherently illuminated system while allowing spatial filtering of the zero-order frequencies of each semi-point source image. This offers the enhancement capability of a single point source system while reducing the coherent noise in the image.

The MTF of each of the semi-point sources is similar to these MTFs shown in Figures A1-5 except the sharp edges on the plot are somewhat rounded because of the partial coherence of a semi-point source.

Figure A1

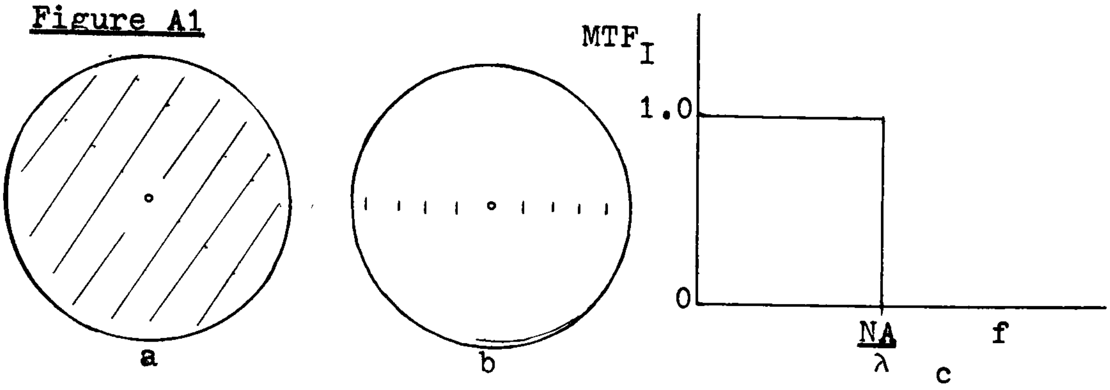


Figure A2

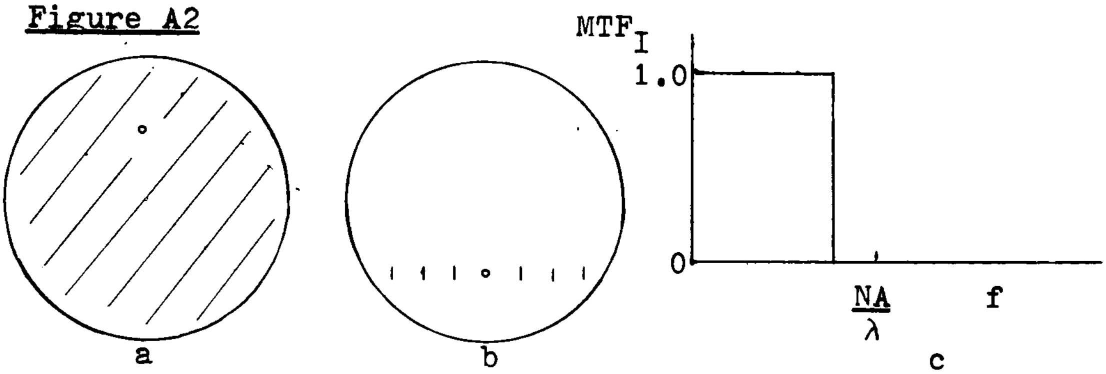


Figure A3

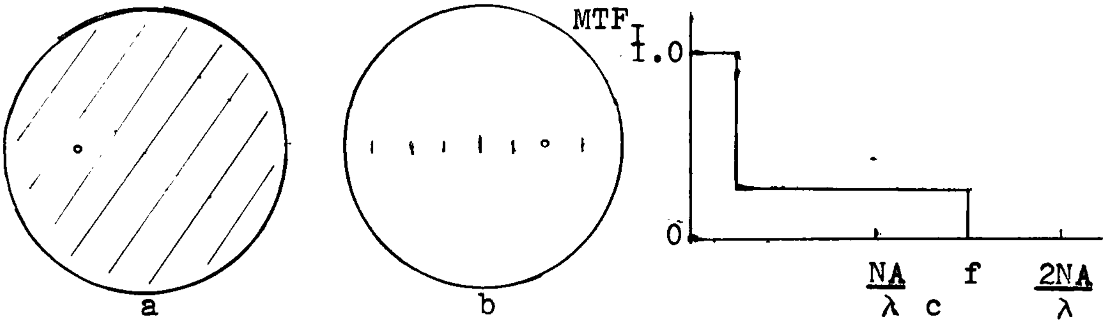


Figure A4

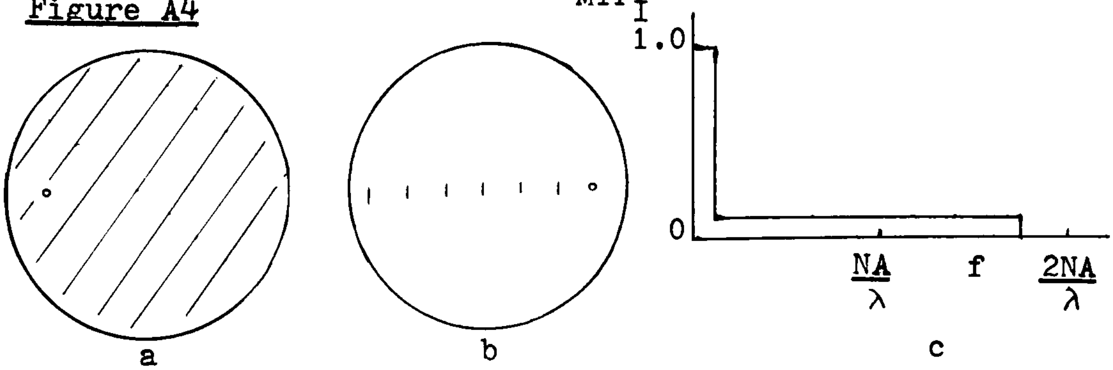
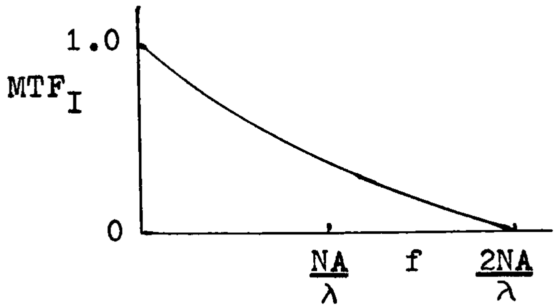


Figure A5



Appendix C Processing of Photographic Plates and Films

Kodak High Resolution Plates

Processed in a 5 x 7 in. tray under a Kodak No. 1 safelight.

1. Develop in DK-50 for 3 minutes at room temperature, using tray rock agitaion 5 seconds every 30 seconds.
2. Kodak SB-1 stop bath for 10 to 15 seconds.
3. Kodak F-5 Fixer for 5 minutes. Lights on after 2 minutes.
4. Water wash for 10 seconds.
5. Kodak hypoclear diluted 1 to 4 for 2 minutes.
6. Water wash for 15 minutes.
7. Dabbed with a photogrphic sponge and air dried.

Kodak Commercial Film No. 6127

Processed in an 8 x 10 in. tray under a Kodak No. 1 safelight.

1. Develop in HC-110 dilution B for 5 minutes at room temperature using tray rock agitation 5 seconds every 30 seconds.
2. Kodak SB-1 stop bath for 10 to 15 seconds.
3. Kodak F-5 Fixer for 10 minutes. Lights on after 3 minutes.
4. Water wash for 10 seconds.
5. Kodak hypoclear diluted 1 to 4 for 2 minutes.
6. Water wash for 15 minutes.
7. Dabbed with photographic sponge and air dried.

Appendix D Overmodulation

Overmodulation is a phenomenon which occurs when the modulation of a sine wave image is enhanced to greater than a modulation of 1.0. In a photograph this appears as a phase inversion of the image detail contrast, i.e. areas of the image that should normally have little density may have a dark area in the middle of the light area, or may be completely dark, depending on the extent of the overmodulation.

Figure D shows a normal sine wave image with mean intensity, $\bar{I}$.

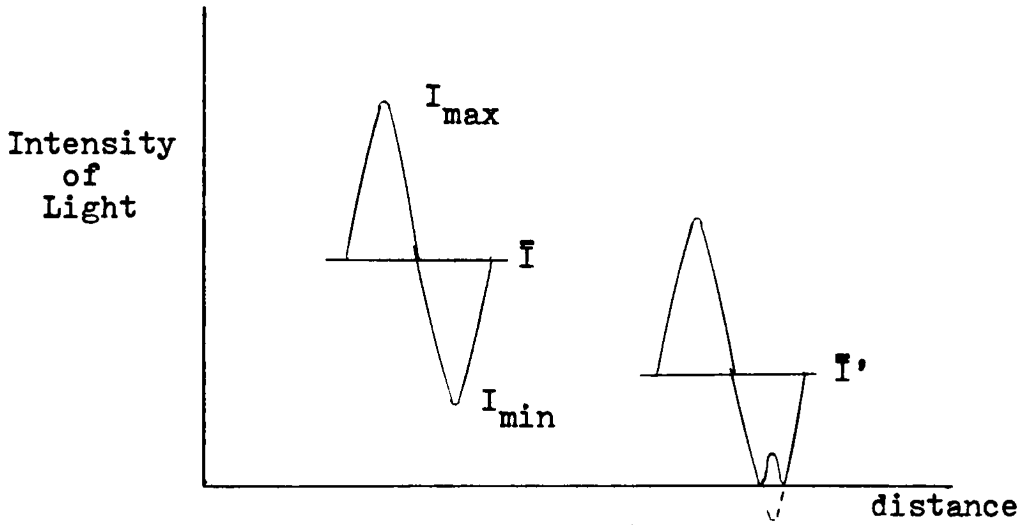


Figure D

Spatially filtering the zero-order diffraction spectrum will not only increase the modulation of the sine wave, but will also lower the mean intensity, $\bar{I}$. A very dense spatial filter may lower $\bar{I}$ to a point where the minimum intensity of the sine wave $\bar{I}_{min}$ will be a value below zero intensity. At the point where the sine wave becomes zero, a phase inversion occurs and the sine wave increases in intensity. Because this inverted "bump" increases in intensity, greater exposure than predicted is given to that area of the image plane, giving more density.

This phenomenon is greatest in the coherent noise on the image because the dust on the negative appears to be completely opaque to the light in the system. This dust speck represents a very high frquency sine wave with a high contrast, usually much higher than the picture detail. When enhanced, this already high contrast increases while the mean intensity decreases. The resulting phase inversion is then much greater than in the picture detail and will be evidenced on the image even when no overmodulation has occurred in the image detail.

Using a low contrast negative will also minimize the occurrence of overmodulation in the photographic detail.